Combining Experimental Data, CFD, and 6-DOF Simulation to Develop a Guidance Actuator for a Supersonic Projectile

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Outline

- Why guided bullets?
- Initial Results
- Wind tunnel results
- CFD
- Subscale Range Tests
- Comparison with CFD and Reconciliation
- Full Scale Range Tests

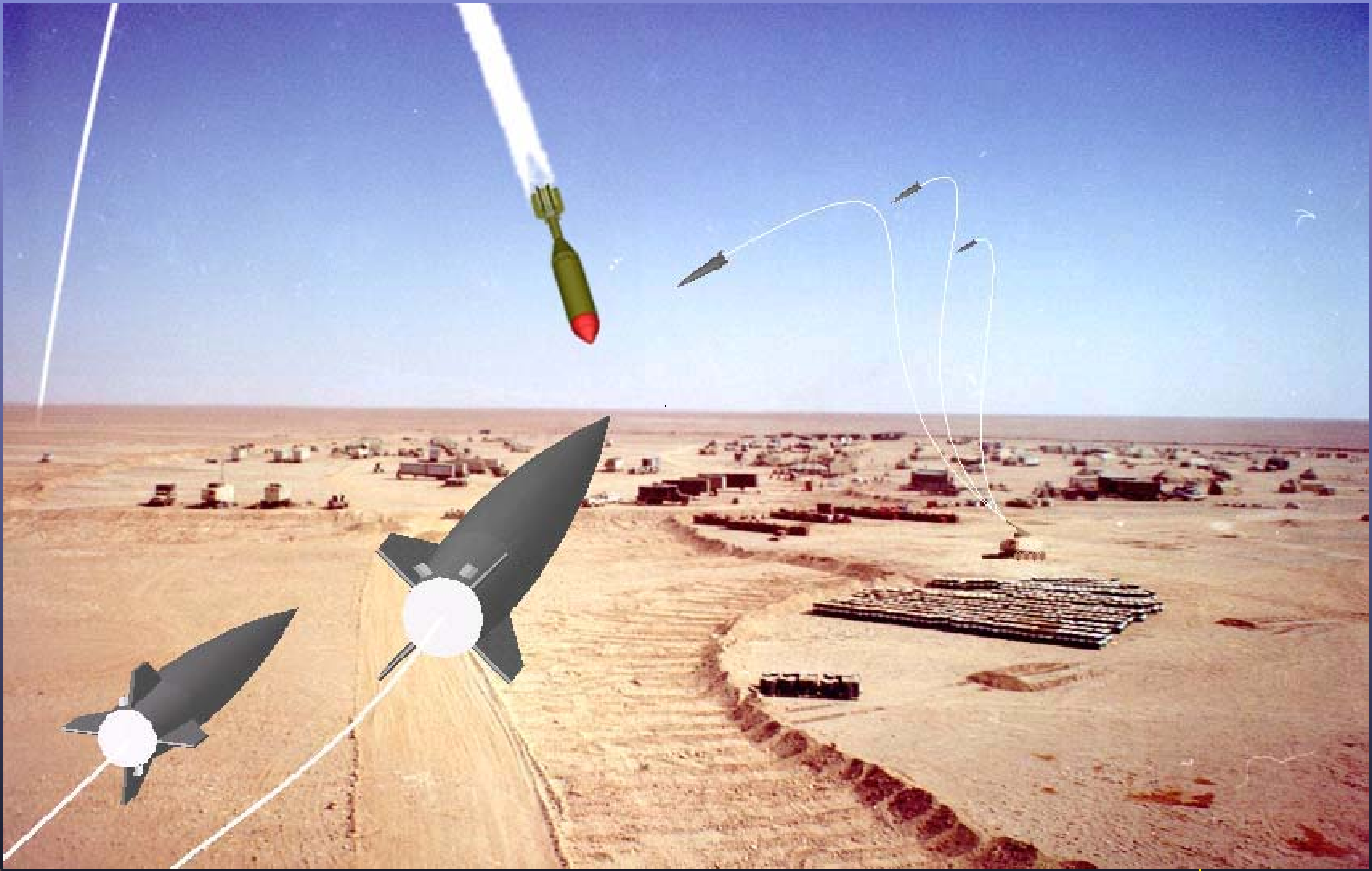
Swarmers Concept for Cruise Missile Defense

Goal: Defend against maneuvering cruise missiles.

Features:

1. High supersonic projectiles (Mach 4+)
2. High g maneuvers (50g)
3. Short Mission (4 sec)
4. Swarm of Projectiles

Guided bullets to intercept mortars



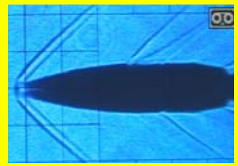
GTRI Phase 1 Efforts

Ball M33 Lab Tests

Optical Verification of changes in flow due to mass injection at

Nose

Midbody



Measurements of mass flow required to affect flow

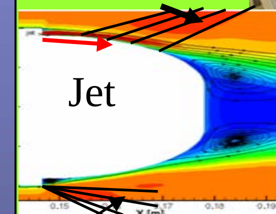
Can Alter Flow

40mm Scaled Ball M33

USAFA Tunnel / CFD

Mass Injection : Nose, Midbody, Boattail

Long and Short Boattail



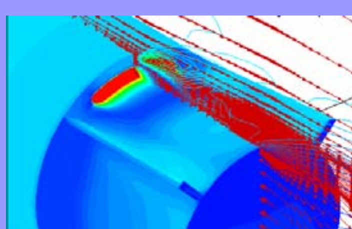
Long Boattail Best

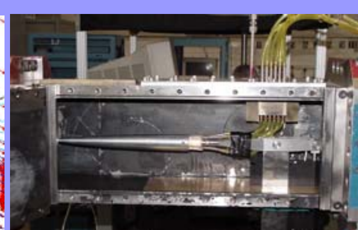
Aft Mass Injection Best

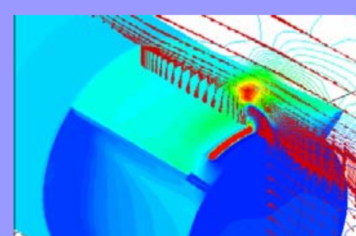
40mm ARL Projectile

U. Texas Tunnel / CFD – forces and moments

Aft Mass Injection : Tangential and Normal







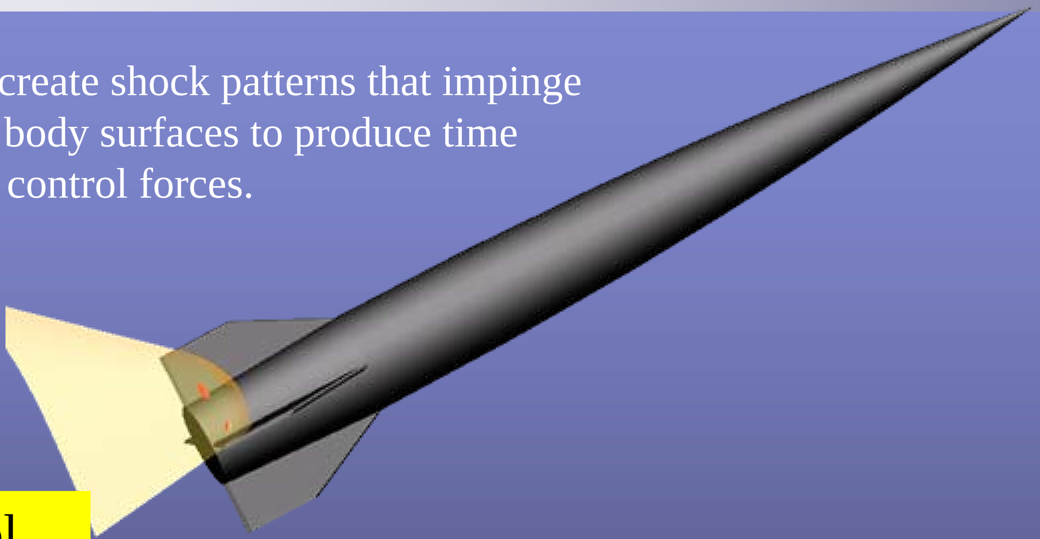
Normal Mass Inject Better

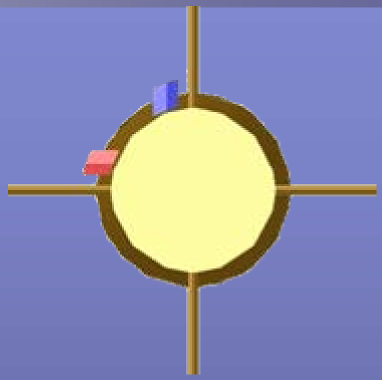
Projectile Unstable

GTRI Second Year Efforts

Concept of implementing flow control near fin

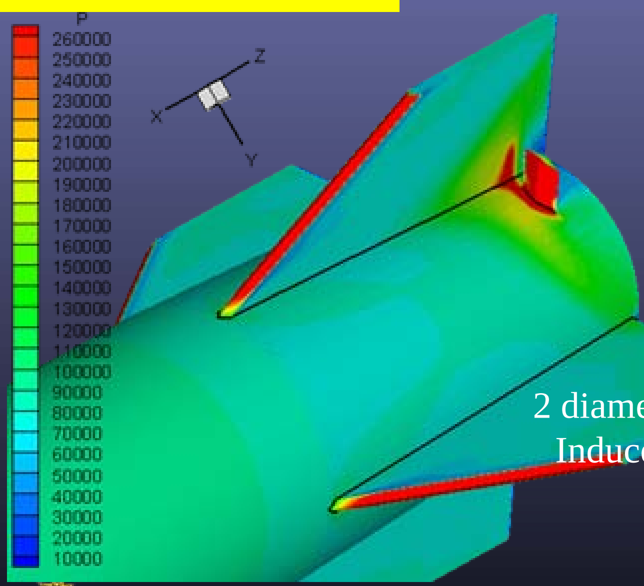
Actuators create shock patterns that impinge on fin and body surfaces to produce time dependent control forces.





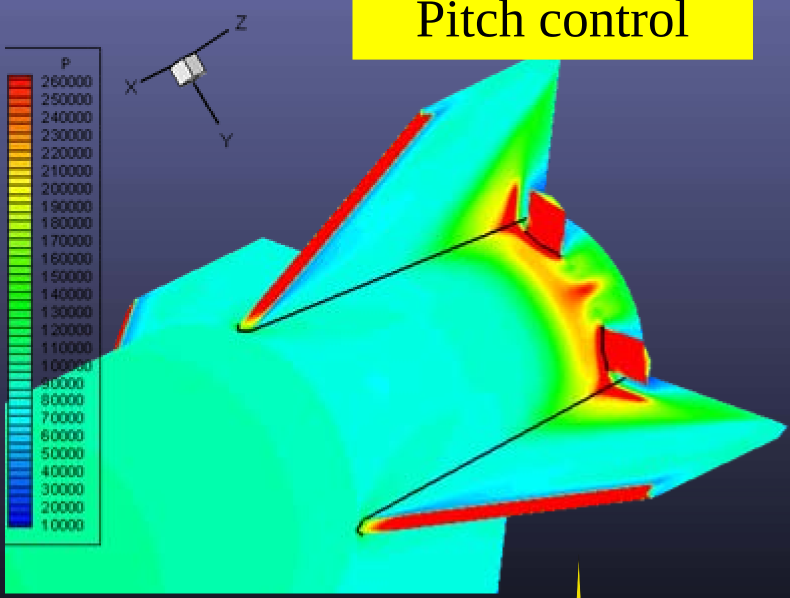
Aft View
2 pins close to adjacent fins
Induce Angle of Attack Change

Roll control



Aft View
2 diametrically opposed pins
Induce clockwise rotation

Pitch control



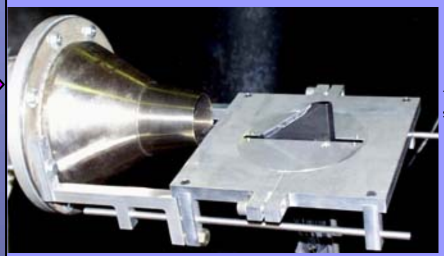
M = 4.0
AOA = 0°

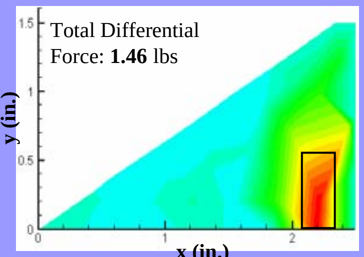
GTRI Phase 2 Efforts

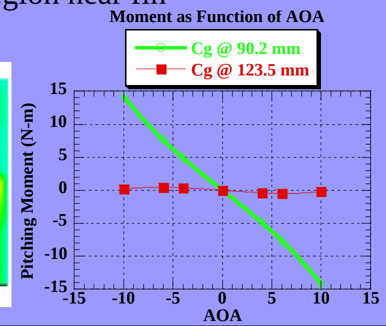
Fin Interactions

GTRI Tunnel

Measured forces generated by pins and mass injection in region near fin







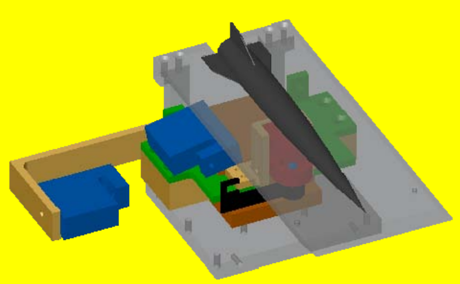
Pins Near Fins Generate Strong Turning Moment

Too Much Volume Required for Mass Injection

Input from ARL on Size, Shape, Mass Dist.

Need System Study to Define:Cg location
Fin Shape/Size
Roll or Fin Stabilized?
Actuation Concept and Preliminary Design

½ Body Test Rig



3D Effects

Steering Force (Steady & Unsteady)

CFD

Understand Fluid Dynamic Interactions

Preliminary Actuators

Available Steering Force

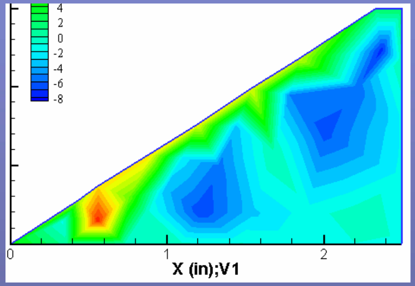
Fire Round at ARL

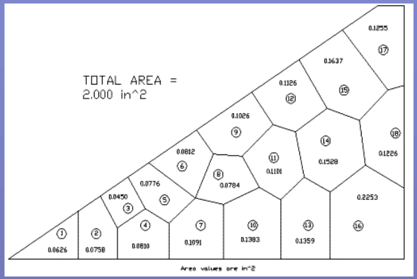
Test Concept and Hardware

Understanding Fin-Body Corner Flow Interactions

Flow over fin and cylinder

Creates pressure changes on fin

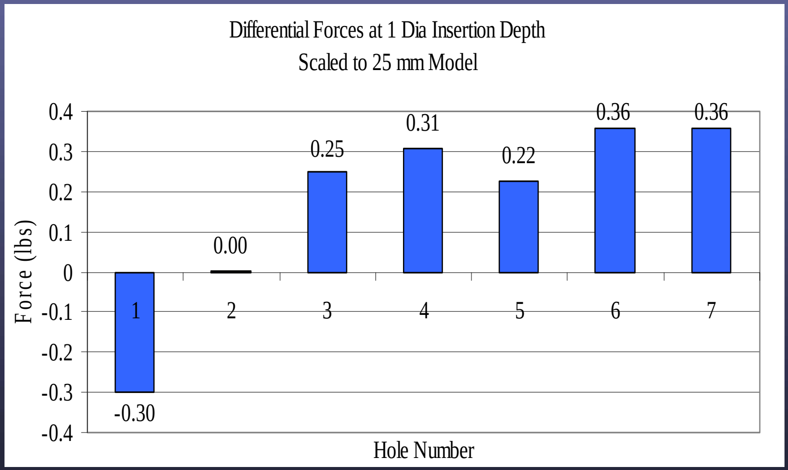


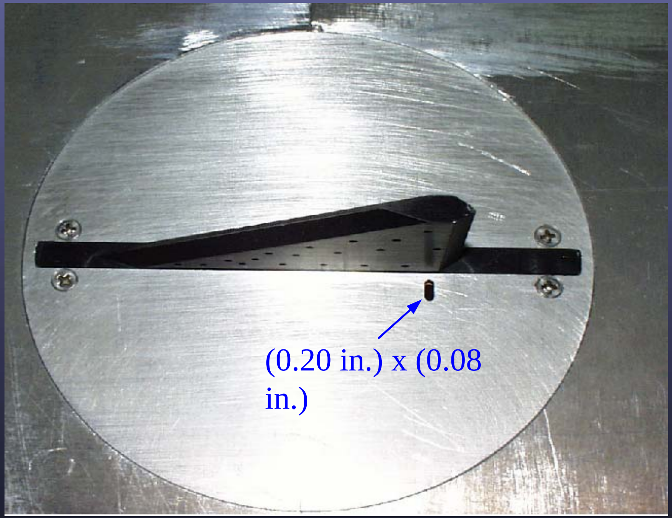


Pressures used to calculate force on fin

Early results proved two things:

1) More force produced near trailing edge of fin





2) Mass flow requirements for fluid injection too high

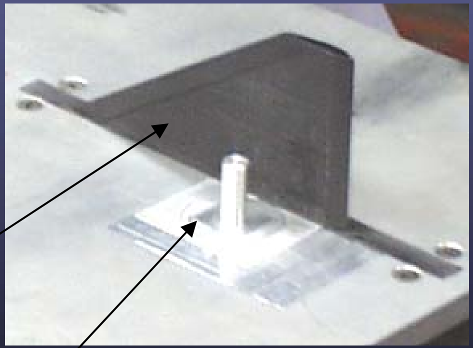
Pin-Fin Interaction Parametric Study

- **Goal:** Understand trades of pin location and pin shape
- **Rationale:** Recognize likelihood of non-optimal pin placement and geometry
  - Data acquired at M = 1.7
  - Data for 4 different pin geometries
    - Round pins 0.1 and 0.2 inch diameter
    - Flat pin with same frontal area as 0.2 round pin
    - Trapezoidal pin with same frontal area as 0.2 round pin
  - Pin height fixed at 0.5 in
  - Spacer blocks used to position pin

Experimental Setup

Rectangle 0.2 | Round 0.2 | Round 0.1 | Trapezoid

Fin



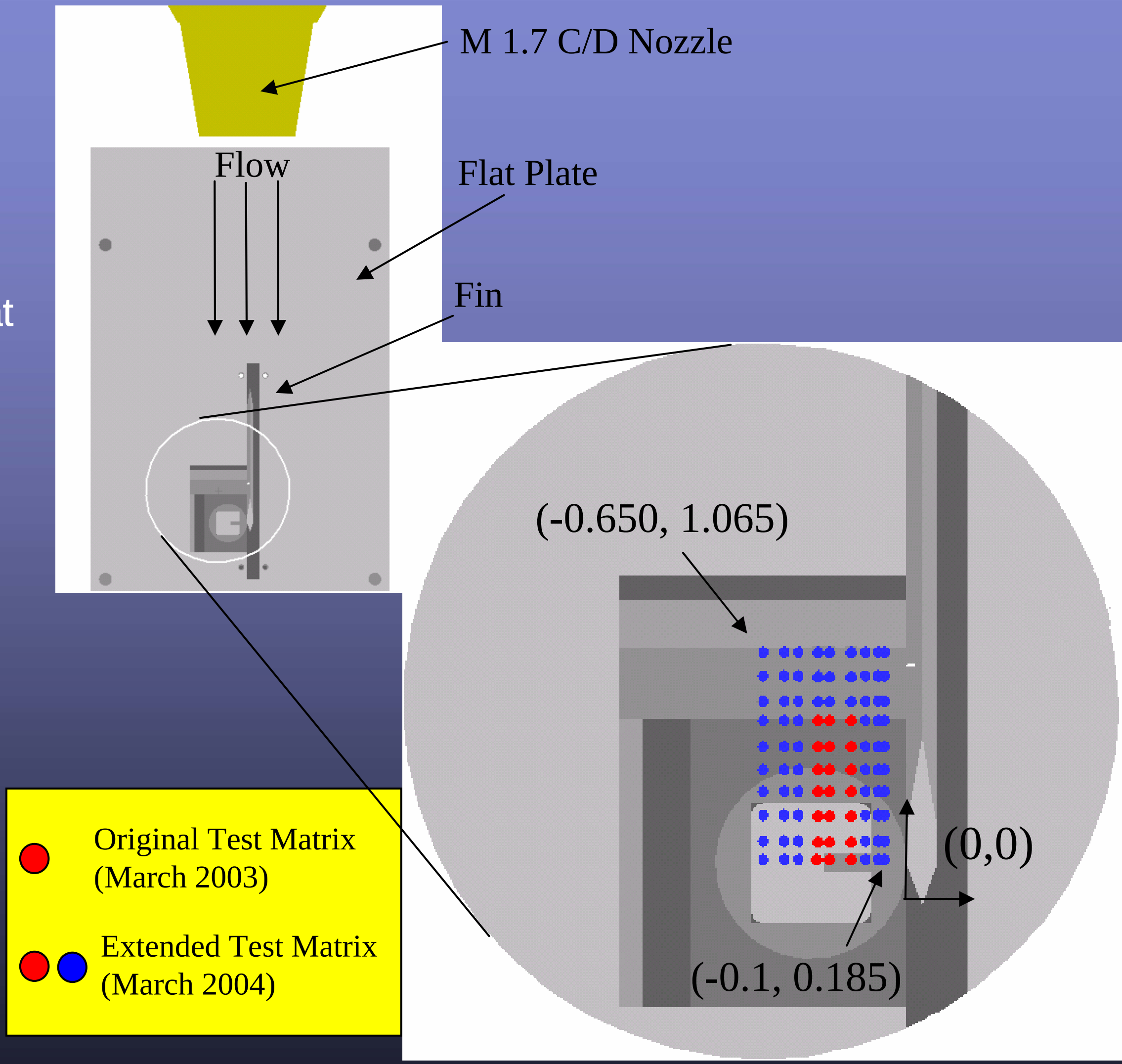
0.2 Round Pin

Parametric Study Details

Pin location test matrix

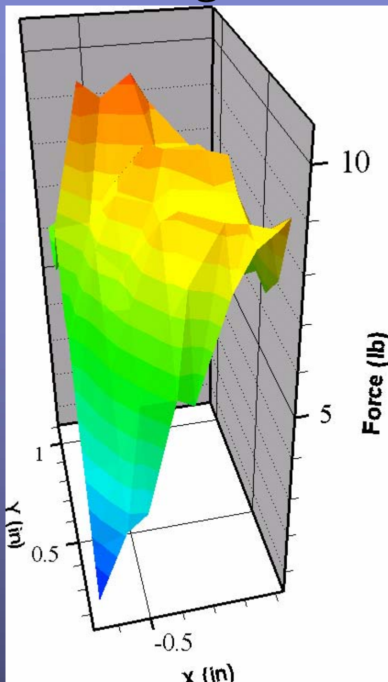
- 9 x 10 Matrix (90 locations)
- 0.55 in spanwise x 0.88 in streamwise
- Force measurements made for all pins at all points except trapezoid, which experienced structural failure
- 271 unique tests performed
- 1300 + data points (each location performed 3 times)

Forces on fin directly measured as opposed to pressure measurements

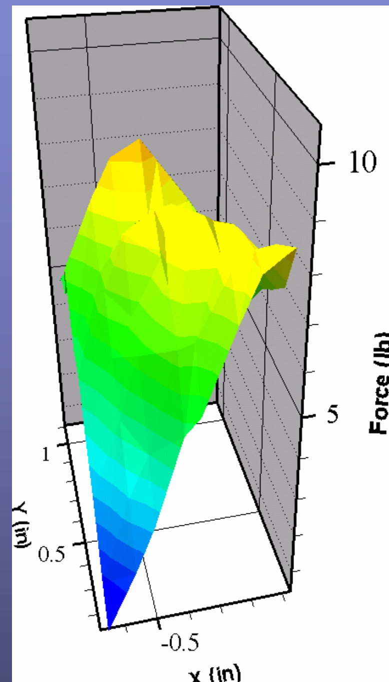


3-D Contours of Force Data

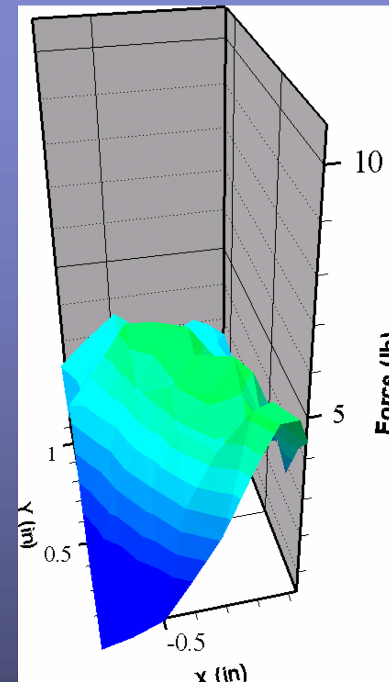
Rectangle 0.2

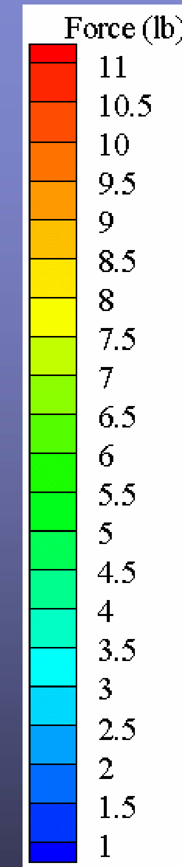


Round 0.2



Round 0.1

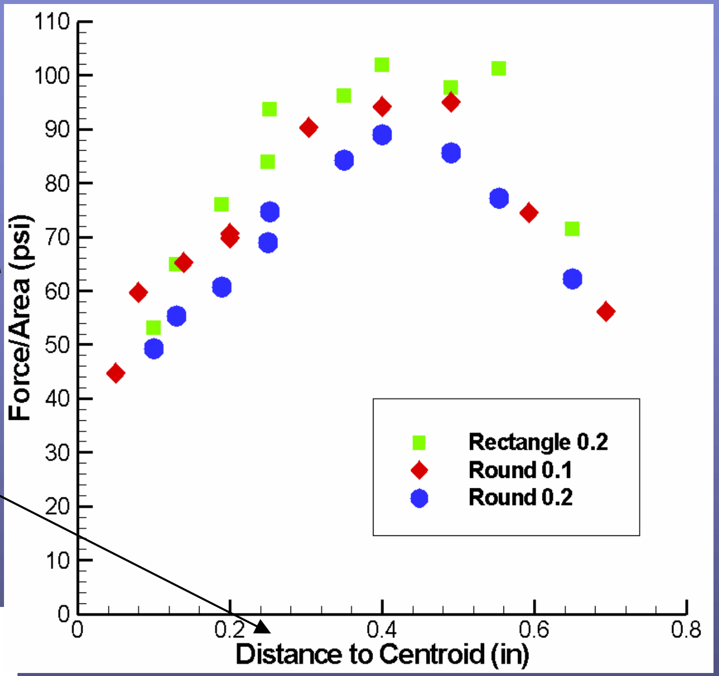


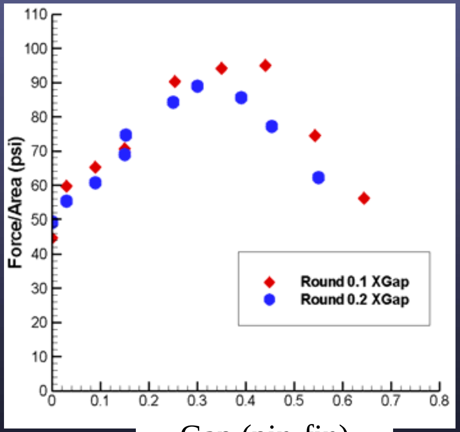


- Contour plots of side force vs pin location show same trend for all pins
- Clear evidence of optimal regions for pin location
  - Implies there is leeway in placement of pin
  - Important as mechanical/space restrictions may not allow for location at optimal location Relative force for flat pin larger than round with same frontal area
  - This likely due to stronger shock (no 3-D relieving effect)
- Hypothesis that optimal location should scale with pin diameter, was proven wrong (compare 0.1 and 0.2 dia pins)
  - The 3-D shock interactions are complex and do not lead to simple scaling

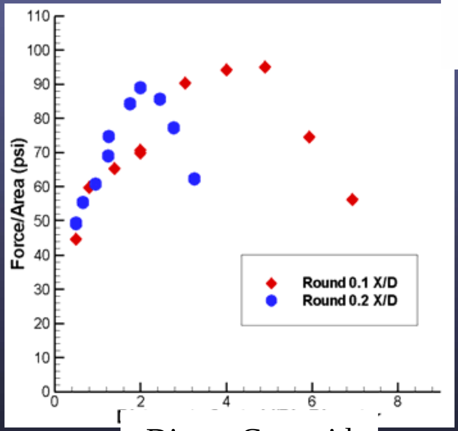
Effect of Separation Distance (between pin and fin)

- Dividing the force by the frontal area of the pin provides a 1st order collapse of the magnitude
- Several different parameters were explored to determine the effect of separation distance
  - The distance from the edge of the fin to the centroid of the pin provided the best collapse
  - Optimum separation distance appears to be about 0.41-0.42 in
- Plots are at Y = 0.775in

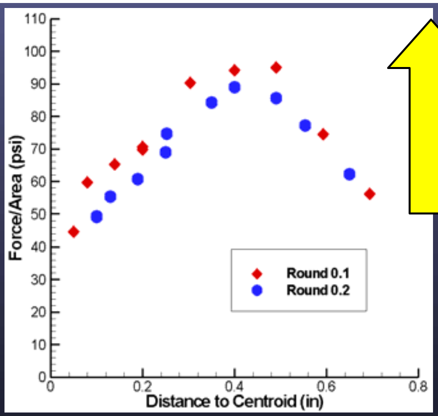




Gap (pin-fin)

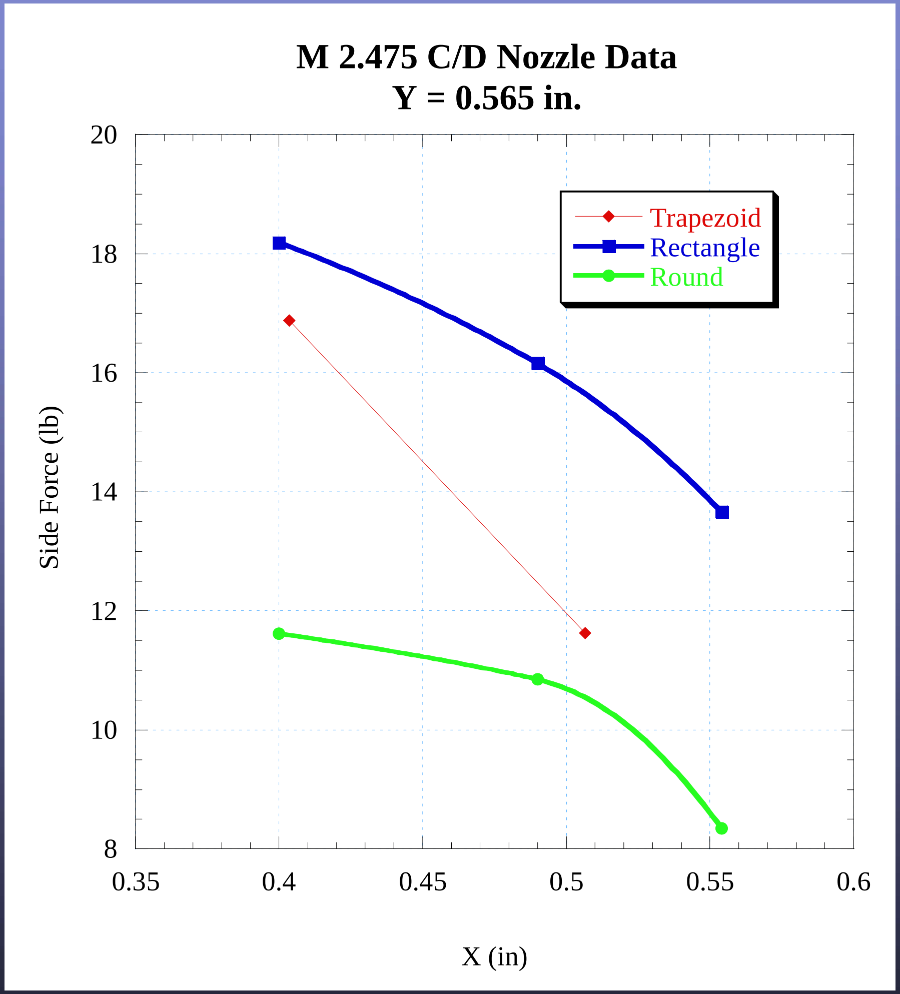


$\frac{\text{Dist to Centroid}}{\text{Pin Diameter}}$

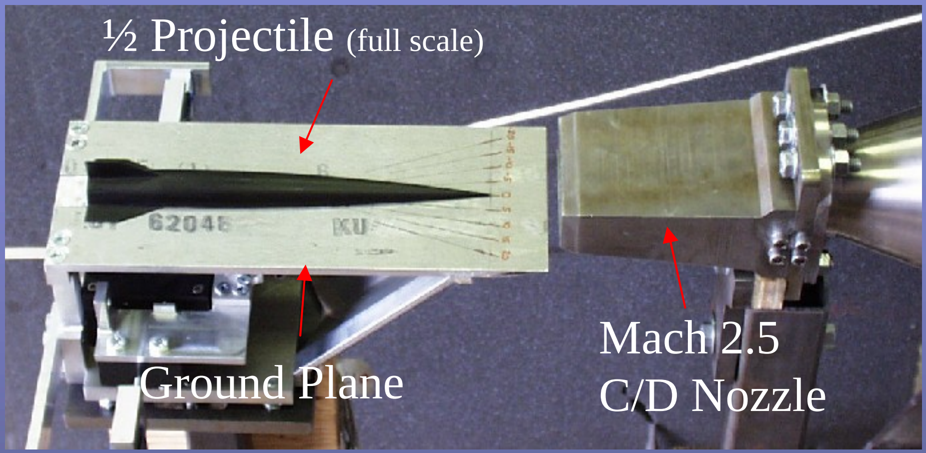


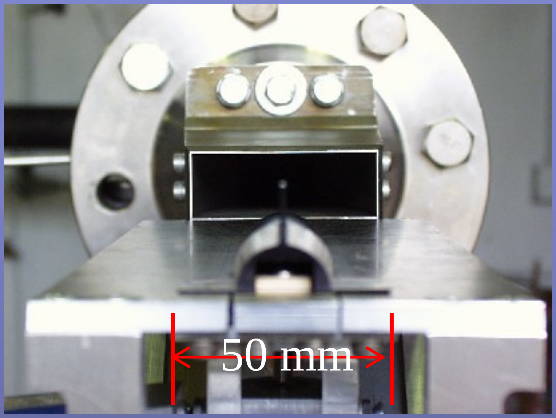
Effect of Pin Geometry

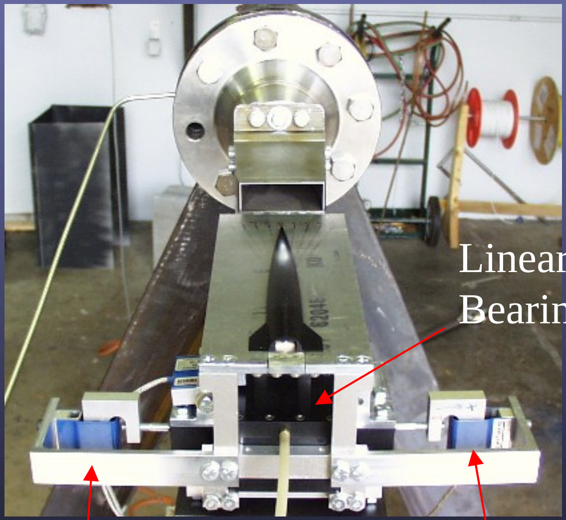
- For same frontal area, rectangular pin gives most force
  - Has least 3-D relieving effect
  - Seems to outweigh additional sideforce generated on trapezoidal pin
- Optimal (X,Y) location independent of pin geometry
- Enough trapezoid data acquired (before structural failure) to demonstrate that flat pin is better



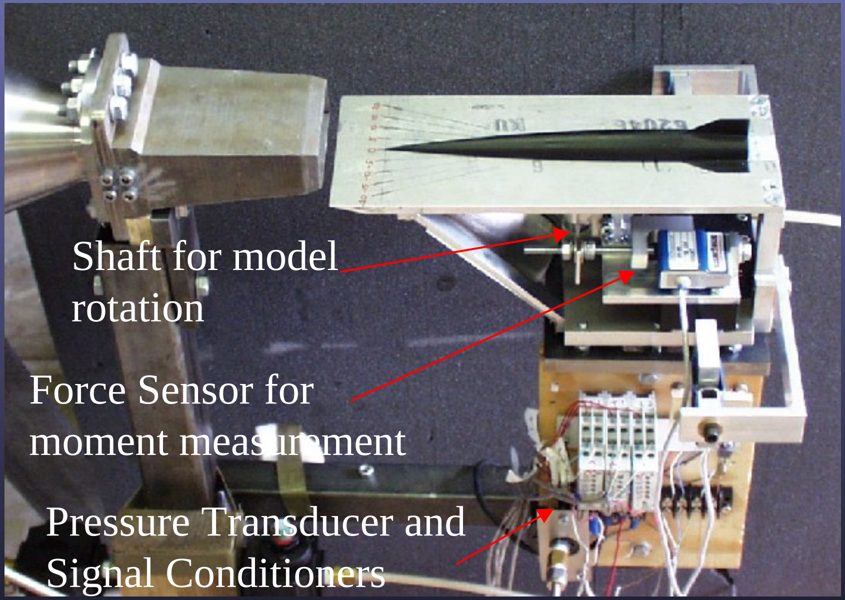
Mach 2.5 Experiments at GTRI



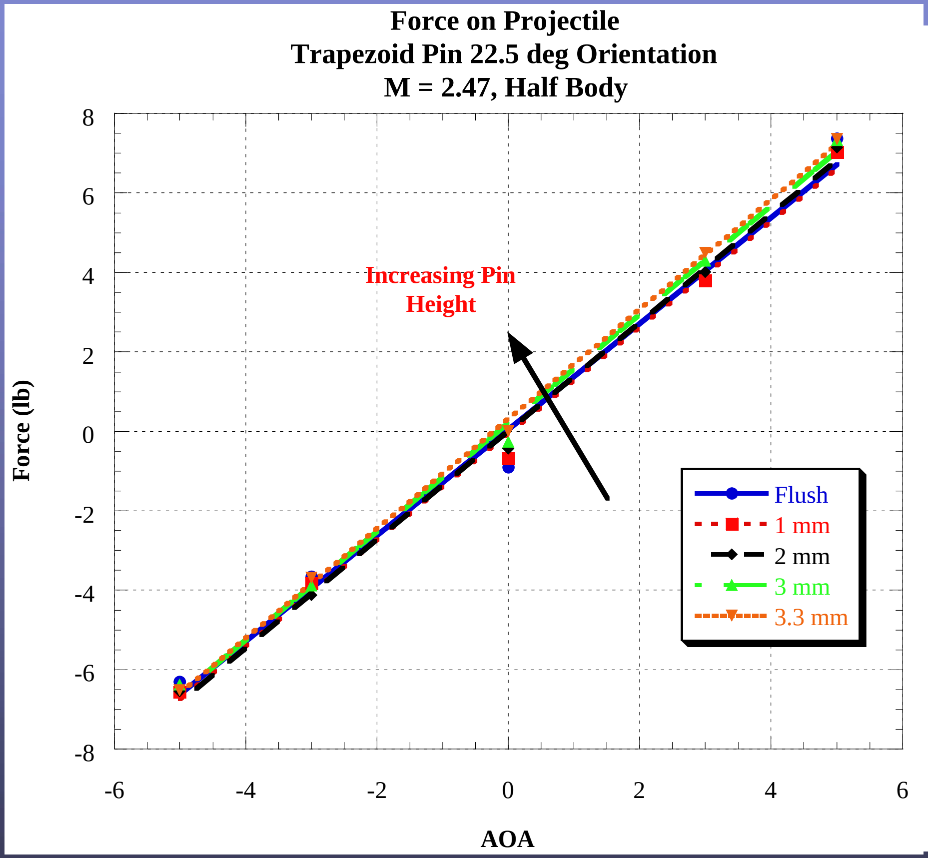


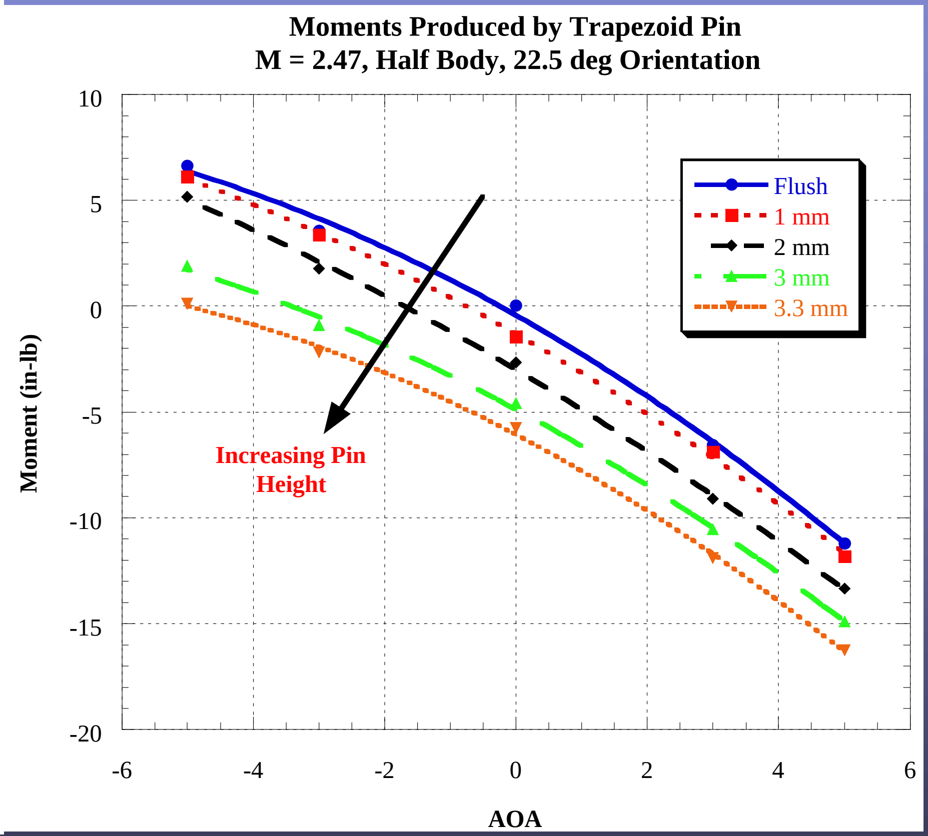


Force Sensors for side force measurement



Effect of Pin Height





- Force dominated by AOA of projectile
- Non linear effect of pin height on moment
- Projectile should be rotate to about 5 degrees with pin deployed

Second Generation Actuator Rotates into Flow

- Rocker Pin Hardware Installed in Wind Tunnel Scale Model
  - Rotation solves stiction problem
- Consisted of
  - Rocker Pin Assembly
  - Pneumatic Cylinder
  - Small Valve
- Further work needed
  - Not g-hardened
  - Valve still too large

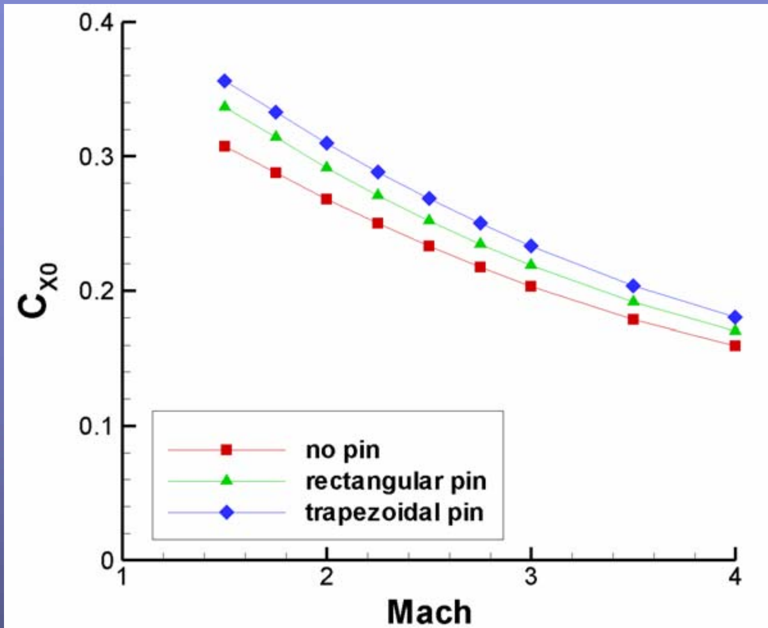
- Using 90 psi
  - Very large holding force
  - Response time on order of 10 ms
  - Rotates projectile over 4 degrees

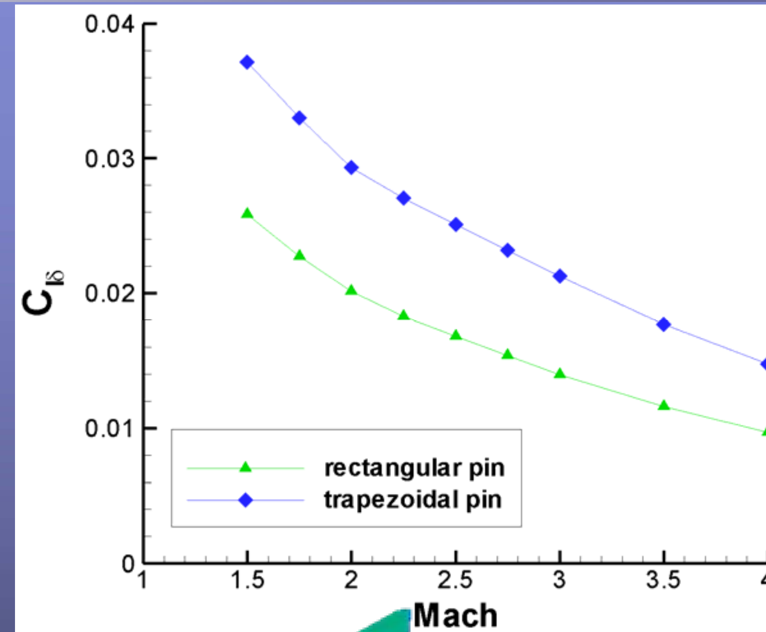
Click to Play Movie

Experimental Input to CFD

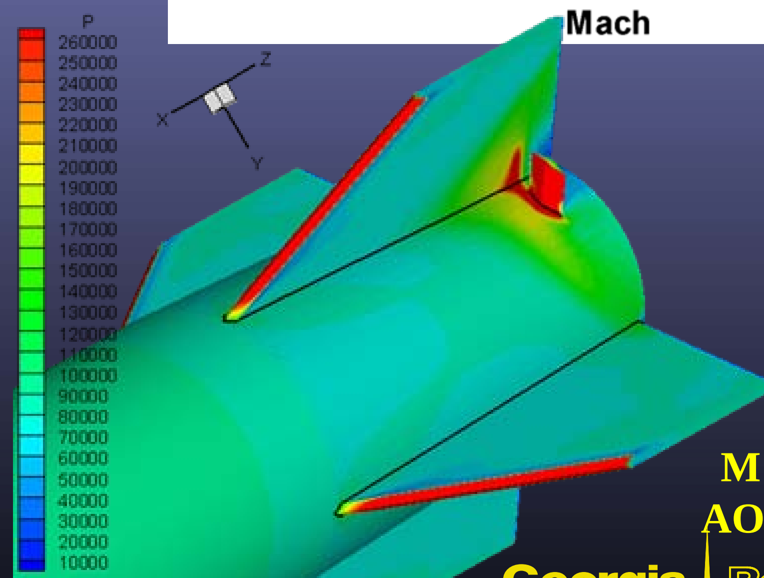
- Experiments showed
  - Where to place guidance pins
  - Effects of pin geometry
    - Including material failure (not from CFD)
  - Crude force measurements
  - Mechanical design considerations (not from CFD)
- Need CFD to complete picture
  - Little flow understanding
  - Better drag and force measurements
  - Use full 3-D body
- Combine EFD and CFD to predict Range Tests

Using CFD to Predict Range Test Results





- **Drag and Roll Torque Predicted using CFD**
  - Allowed for estimation of performance in range
  - Fewer shots required as we knew how many rotations to expect downrange

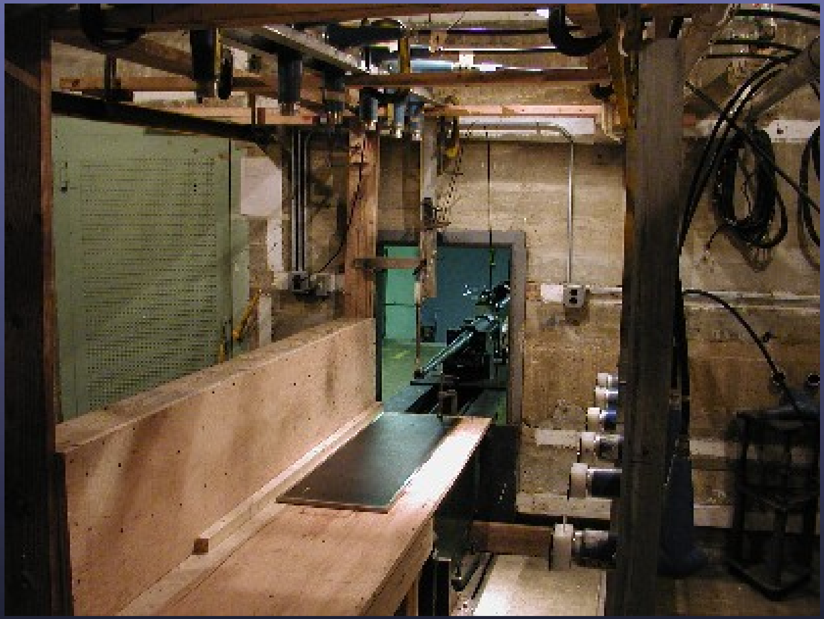


M = 4.0
AOA = 0°

ARL Range Tests to Measure Roll Torque

- ½ Scale Projectiles Fired from 1 inch Gun
  - Quantify Rolling Moments
  - Provide Results for Validating CFD
  - Provide More Accurate Aero Coefficients to 6 DOF

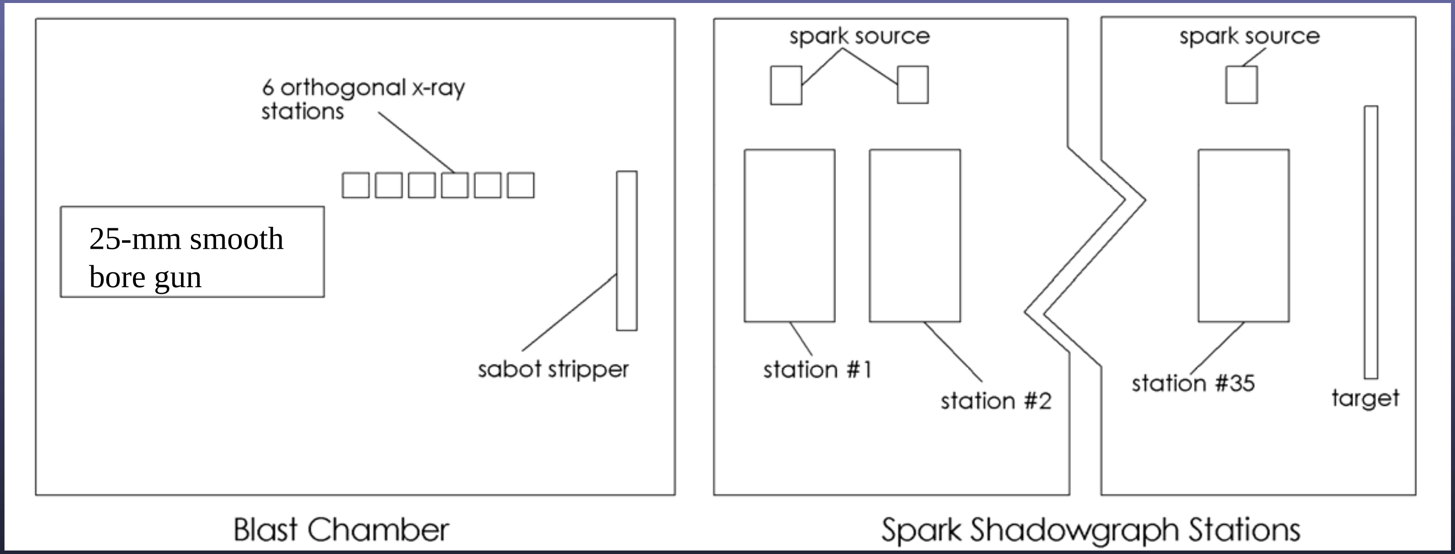
- Total shots fired: 15 rounds
  - 3 with no pins
    - 1 at Mach 3
    - 1 at Mach 2.5
    - 1 at Mach 2
  - 3 with long pins (0.1 in height) at Mach 3
  - 9 with short pins (0.07 in height)
    - 3 at Mach 3
    - 3 at Mach 2.5
    - 3 at Mach 2



Picture of test facility

ARL Range Test Setup

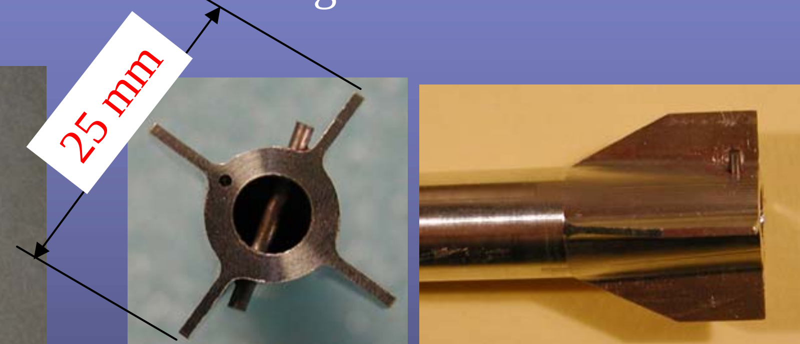
- 6 Orthogonal X-ray Stations Near Muzzle
  - Showed that Sabot Separated Cleanly
- 35 Shadowgraph Stations – to 100 m Downrange
  - Generated Images that were used to determine;
    - Roll and Pitch Damping
    - Drag
    - Number of Revolutions – Spin Rate



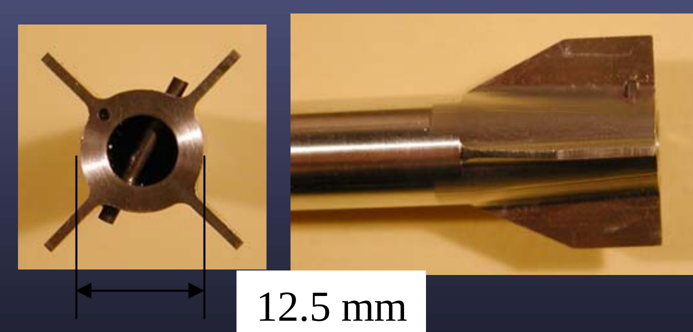
Test Articles

- Projectiles ½ Scale (25 mm)
- Pins were round 1/16th in diameter on opposing fins
- Nylon Sabot

Long Pin Test Article

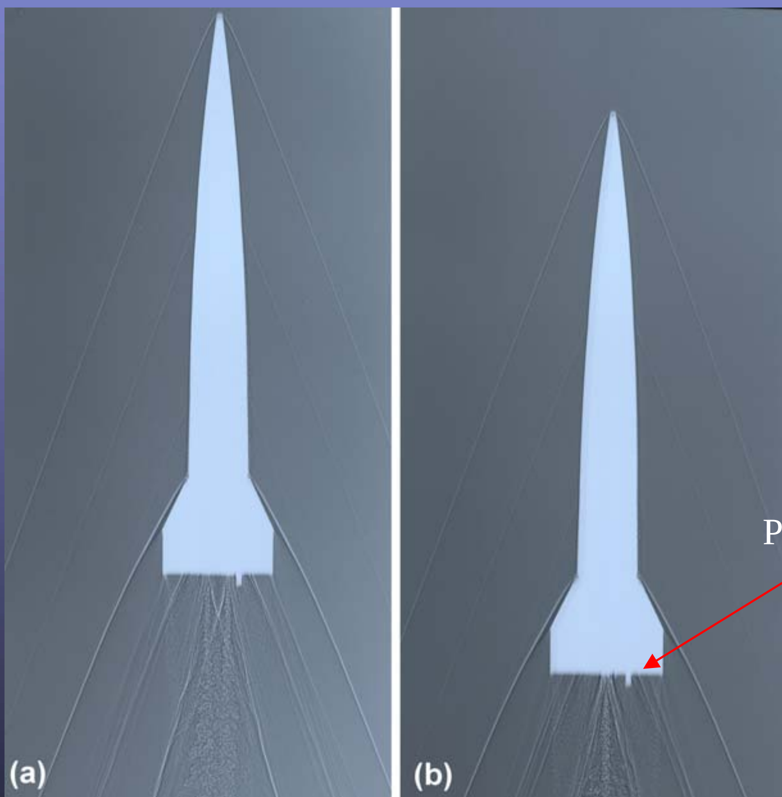


Short Pin Test Article

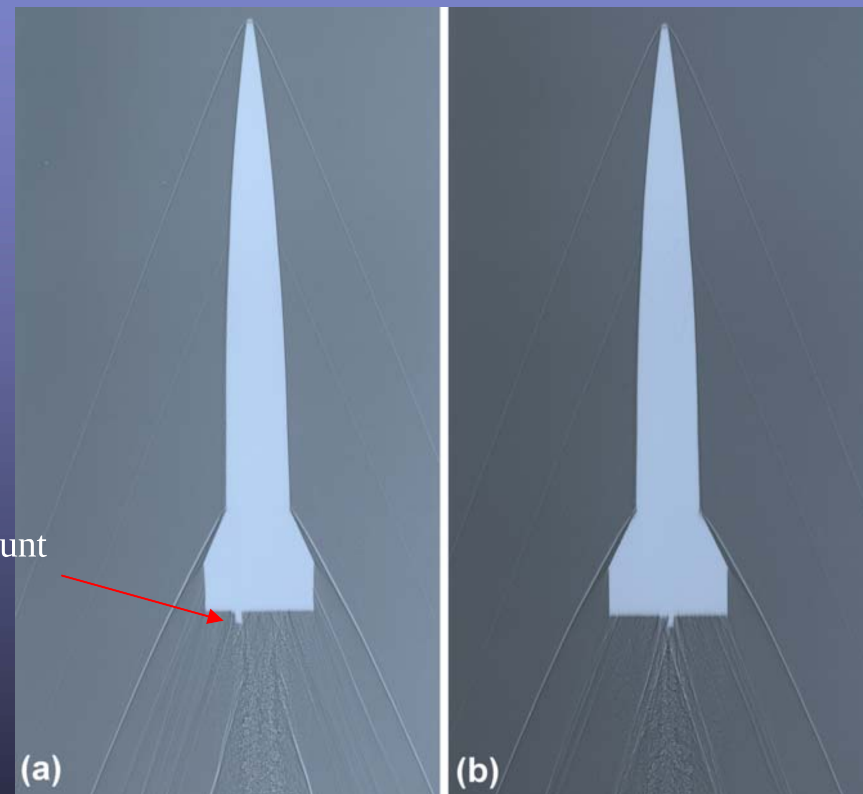


Shadowgraphs from Range – Count Rotations

- The rotation of the round as it traverses the range can be tracked via a spin pin
- The rotation rate leads to a measurement of roll torque developed by pins



Pin Used to Count Revolutions

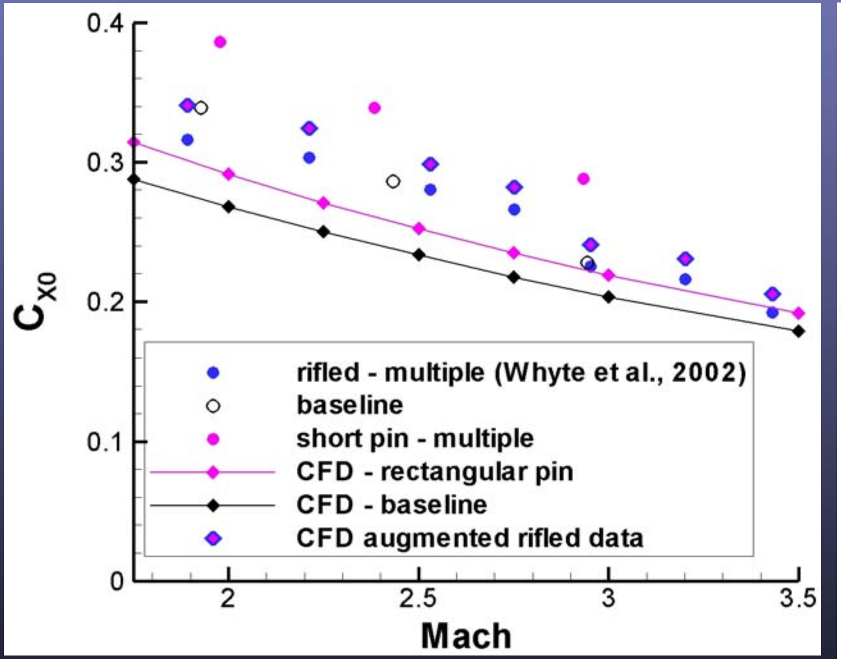


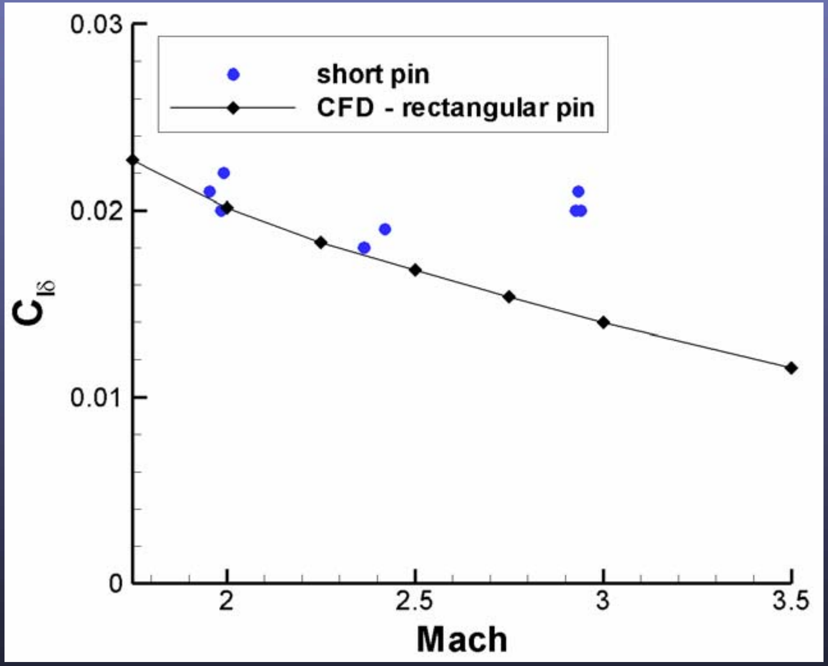
Stations 22 and 27
6.7m to 8.2m
Little Spin Observed

Stations 295 and 300
90m to 91.4m
Over 90° rotation

Range Test Comparison with CFD

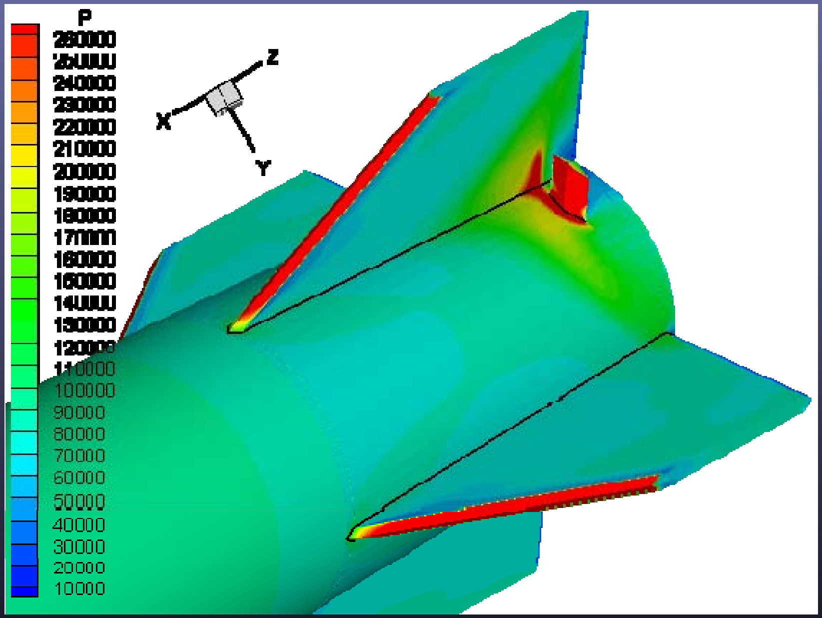
- Comparison with measured data not as good as expected
  - Drag under predicted at all Mach numbers
  - Roll torque prediction worse as Mach number increased

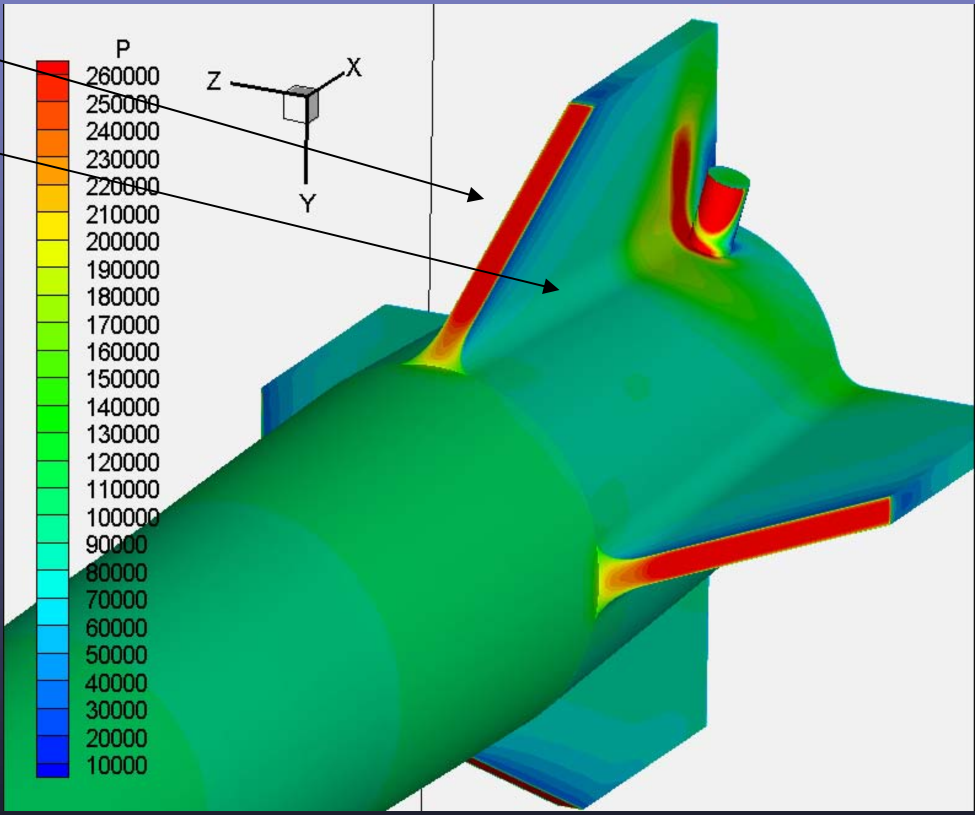




What went wrong?

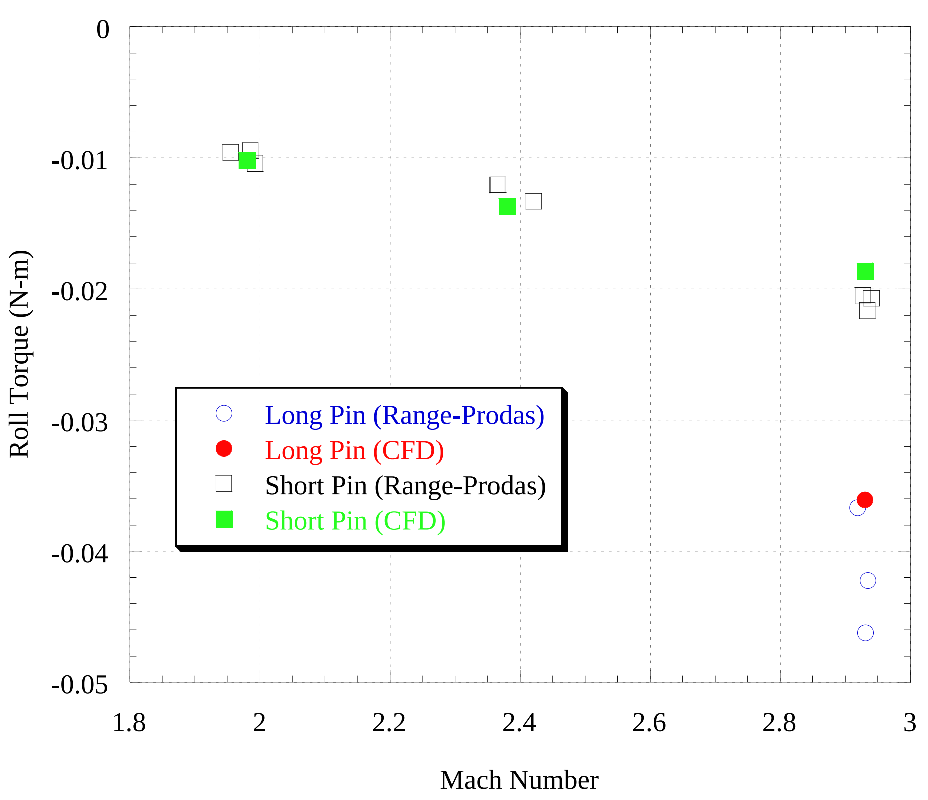
- Compromises in machining small rounds led to significant differences between CFD geometry and test rounds
- New grid generated and new runs accounting for
  - Fin leading edge bluntness
  - Fillet at base of fin
  - Round pin versus Rectangular

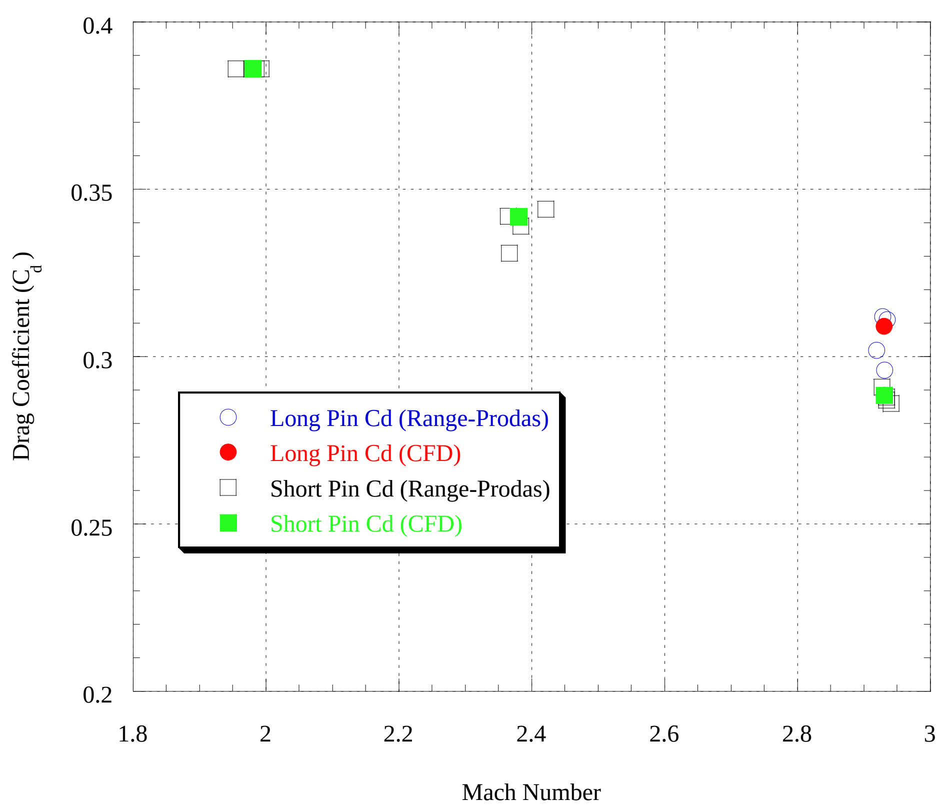




Comparison with Updated Geometry

- Once a more accurate geometry was modeled, a much better correlation was found between the computed and measured drag and roll torques
- Allowed us to proceed with divert test on full scale rounds



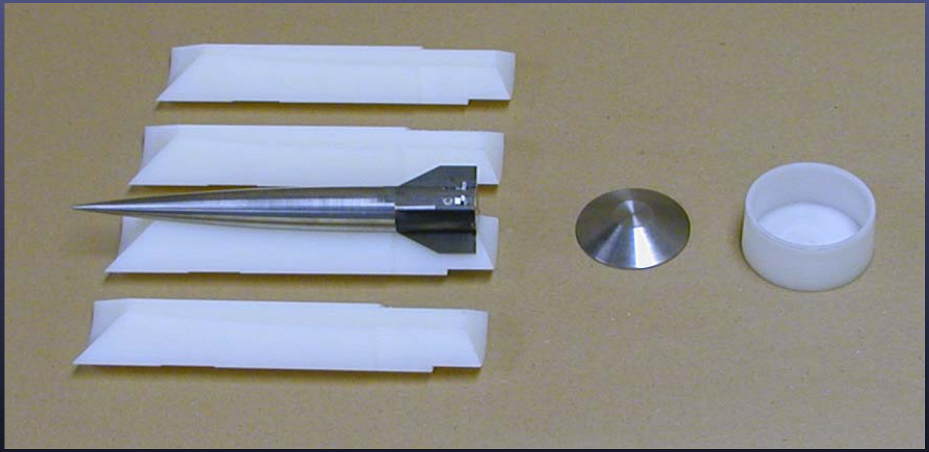


700 ft Range Preliminary Tests

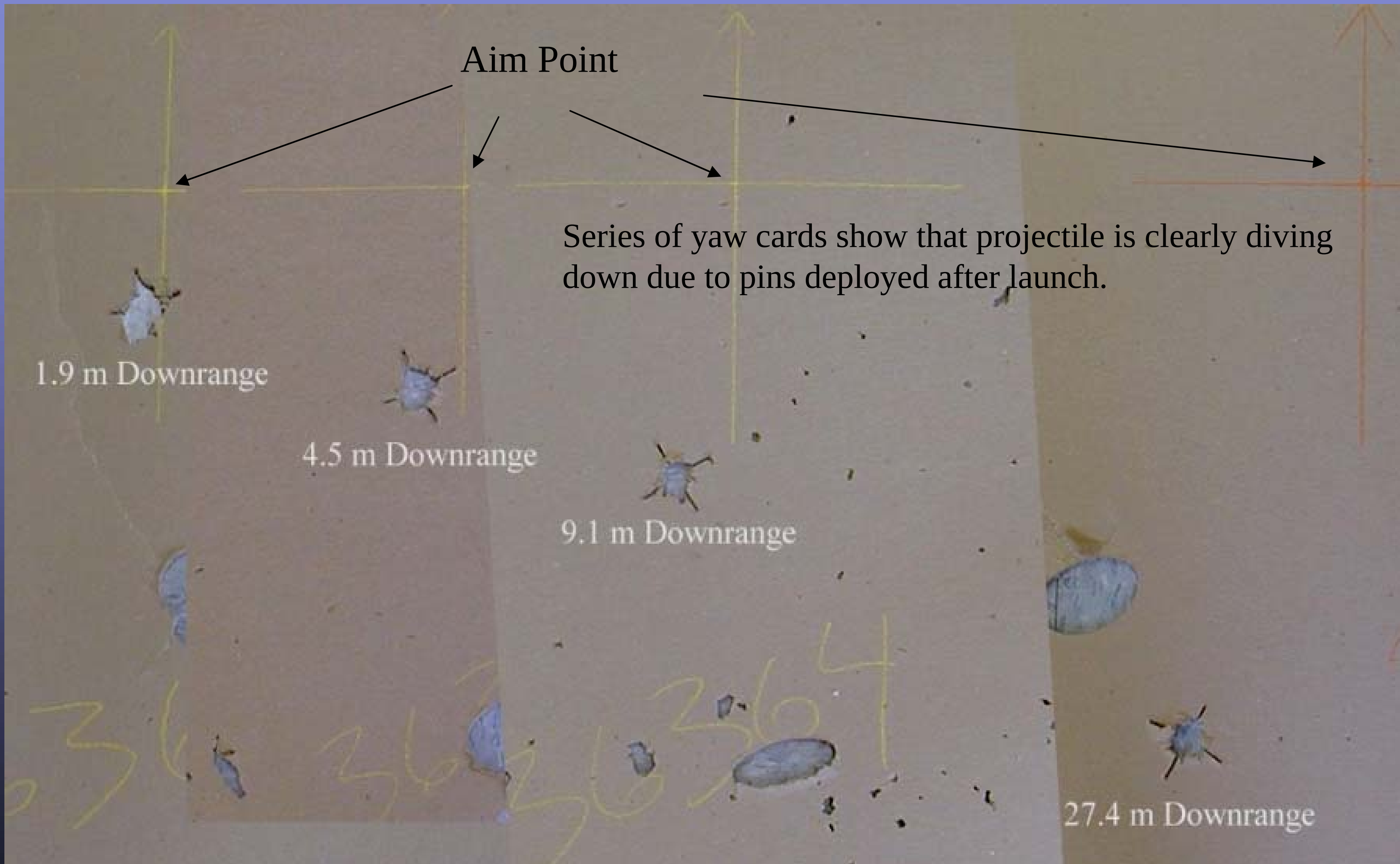
- Outdoor Range
- 75 mm smooth bore gun
- Yaw cards set up
- Problems encountered
  - Stability
  - Sabot Separation

Sabot and Launch Package Resolution

- New set of rounds made with increased static margin
- Cup scored more deeply
- Aluminum pusher plate

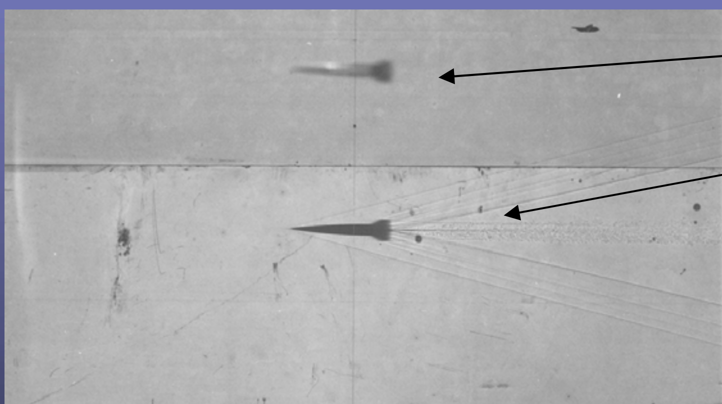


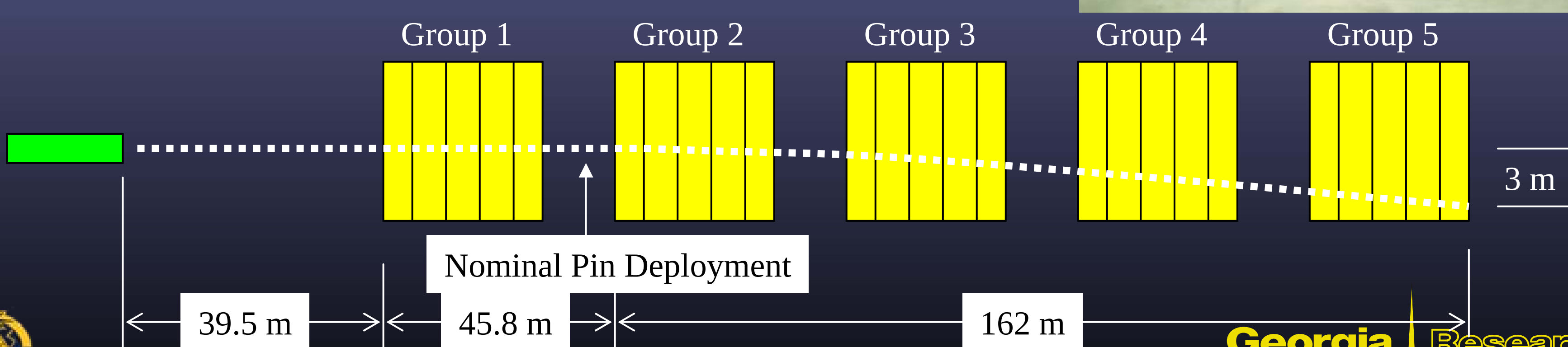
700 ft Range Tests – Divert Demonstration



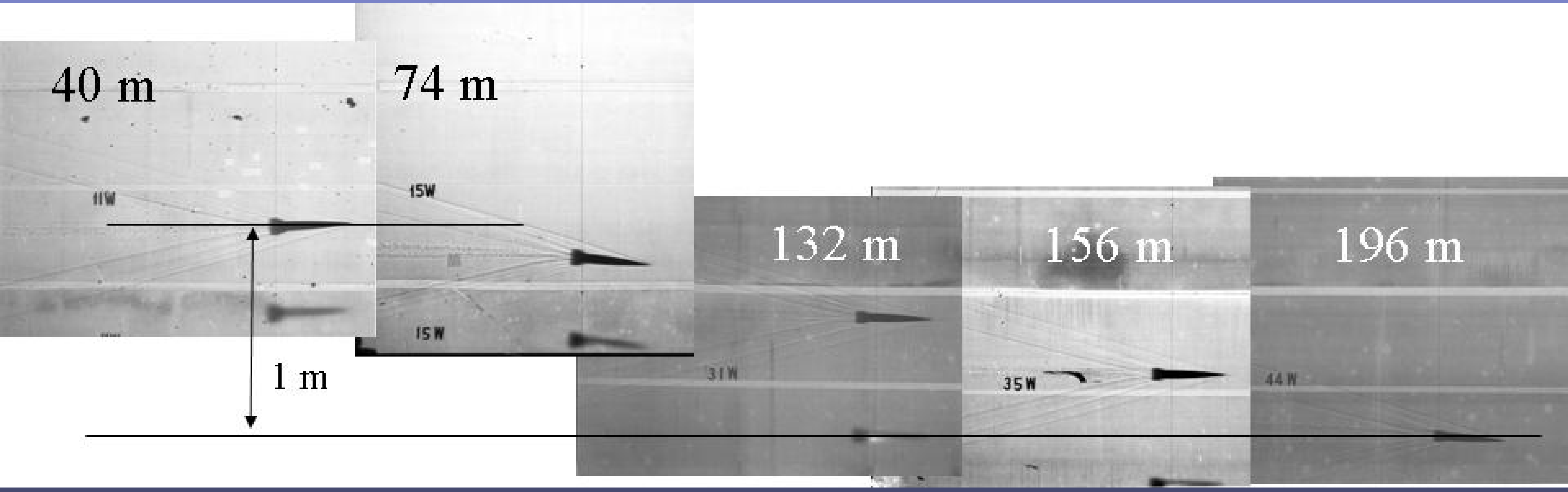
Transonic Spark Photograph Layout

- 5 groups of 5 stations
- Each Station provides Shadowgraphs for
  - Vertical Plane – Wall
  - Horizontal Plane - Pit

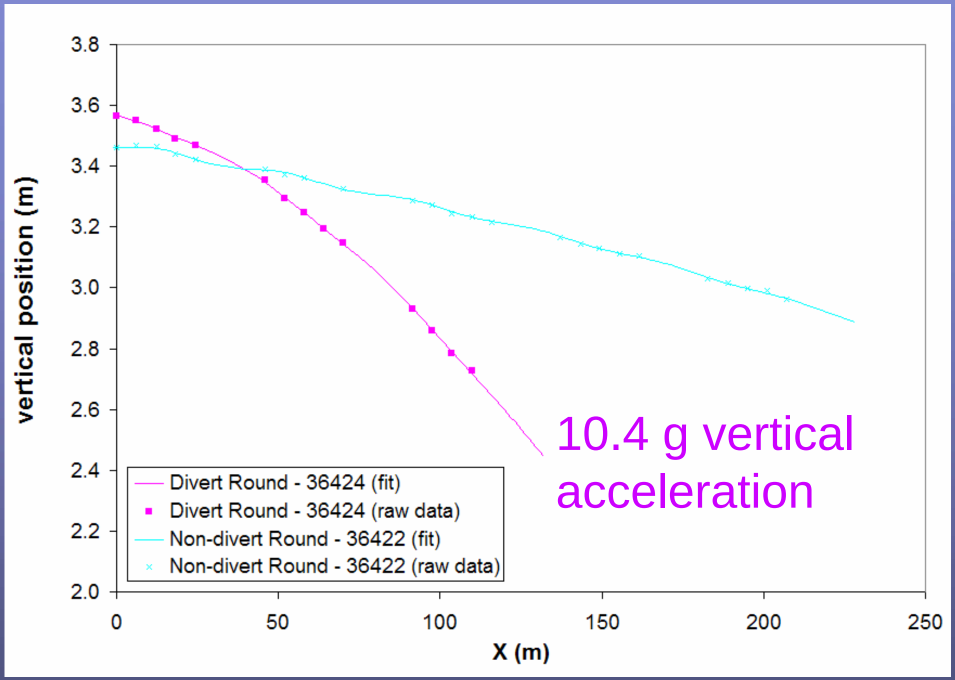




Divert Demonstrated by Shadowgraphs



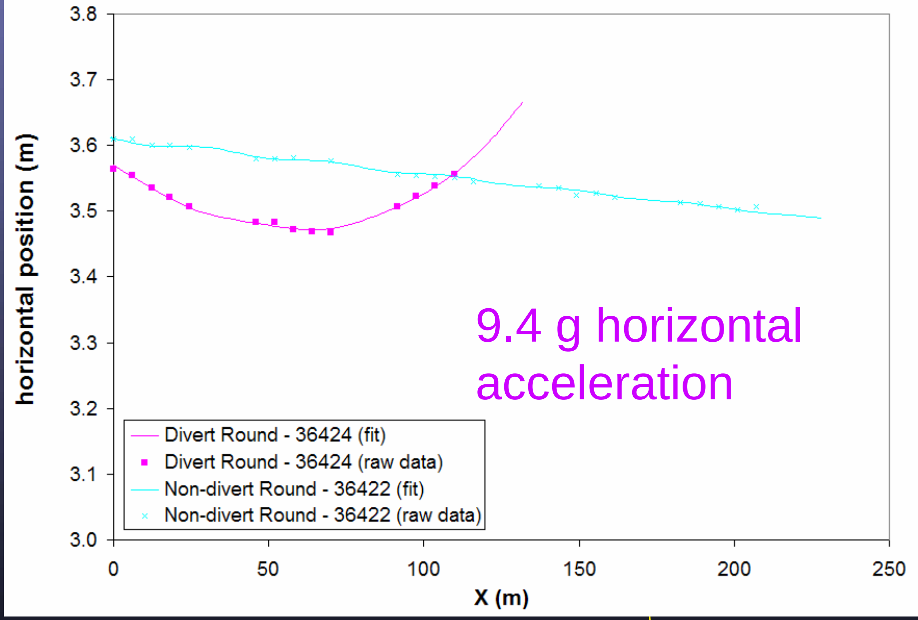
Demonstrated High G Turn on Stable Projectile



Stable projectile for testing (1.5 caliber static margin)

~14 g divert maneuver

~80 N force created by control pins



Preliminary data reduction

More data will be available in the near future

Concept promising for high g maneuvers

Conclusions

- A demonstration of steering a Mach 4 projectile using the guidance pins was successful
- The combined CFD and Experimental efforts led to a greater understanding of the effects of the pins
  - EFD and CFD each used to get different but required forces and moments
    - Results could have been easily done without IFD
  - This in turn allowed us to better predict the results of the range tests
- Less range tests were required because once the predictions were validated, it was proven we understood the aerodynamics
  - This saved substantial amounts of money
    - $10,000 bullets and 5 range operators and 2 PhDs add up fast
    - (As does destruction of the ADT alarm box)

Less Bullets → Less $$ → IFD=GOOD